Post punching behavior of reinforced slab-column connections

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Abstract

Reinforced concrete flat slabs are extensively used in buildings and parking garages. At the ultimate limit state, their design is usually governed by punching shear. In the case where no punching shear reinforcement is provided, failure develops in a brittle manner. Furthermore, punching shear failure of one column may propagate to adjacent columns, eventually leading to the total collapse of the structure. Punching shear failure occurs with almost no warning signs, because deflections are small and cracks at top side of the slab are usually not visible. Over the past decades, several collapses due to punching shear failures have occurred, resulting in human casualties and large damages.

Some solutions can be adopted to enhance the post punching behavior of flat slabs and to avoid progressive collapse. This paper presents some results of an extensive experimental campaign performed at the Ecole Polytechnique Fédérale de Lausanne. The post punching behavior of 24 tested slabs, with various flexural reinforcement layouts are introduced and compared. The performance and robustness of the various solutions is investigated to obtain physical explanations of the load-carrying mechanisms.

1. Introduction

The prediction of the punching strength has been the main object of research on the punching shear, leading to the development of reliable design rules with an acceptable level of safety to be used in design codes[1-4]. However, scanty works are found on the behavior of flat slabs after a punching failure and conditions in which it can lead to a progressive collapse[5-7].

In the late 70's, the punching failure of a slab during the construction phase led to the progressive collapse of a large part of a shopping center in Switzerland, Figure 1a. During the winter of 1981, another collapse occurred at an underground parking garage at Bluche, Switzerland, which caused the death of two children, Figure 1b. In 2004, a catastrophic collapse occurred in an underground parking garage at Gretzenbach, Switzerland. This collapse resulted in the death of 7 firemen, who were extinguishing a fire in the garage. Failure likely started from one column and propagated to a large part of the structure, Figure 1c.

As pointed out earlier, these structural collapses show that there are some shortcomings in current codes of practice. As a consequence, there is a question whether flat plates designed according to current structural concrete codes really fulfill the basic requirements for structural integrity. The failure of reinforced concrete slabs is in most cases ductile, and causes only limited redistribution of loading. Punching failure of flat slabs without shear reinforcement is an exception, and the drop in resistance at failure is considerable and thus leads to a large redistribution of loads, which can trigger failure at adjacent columns and eventually lead to the progressive collapse of large parts of the structure.[8] One possibility to avoid these failures is to provide alternative load paths to transfer the load of a column after it has failed in punching shear. This may be achieved by having some ductility after failure, which can be provided by means of punching shear reinforcement or integrity reinforcement. ACI 318-05[1] recommends that “at least two compressive reinforcing bars in each direction shall pass through the column core and shall be anchored at exterior supports. The two continuous compressive bars passing through the column may be termed integrity reinforcement, and are provided to give the slab some residual capacity to prevent a local failure over a column lead to the progressive collapse of a large part of the structure”.

a) Shopping center « Serfontana », Switzerland, 70’s b) Underground parking garage, Bluche, Switzerland, 1981 c) Underground parking garage, Switzerland, 2004

Figure 1: Structural collapses due to the punching shear failure

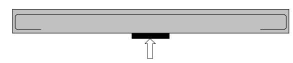
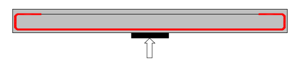
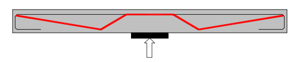
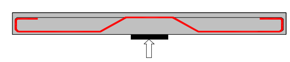
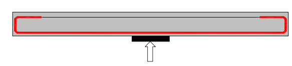
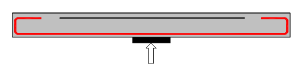
2. Experimental investigation

Three test series on a total of 24 flat plates were carried out at the Structural Concrete Laboratory of the Ecole Polytechnique Fédérale de Lausanne to investigate the post punching behavior of flat slabs supported by columns.[9] The first series investigated the effect of available tensile reinforcement in the negative moment area over the column on the post punching behavior of flat slabs. The second series consisted of eight specimens. Four specimens to investigate the effect of additional straight bars placing on the compression side of the slabs passing through the column and the other four specimens included bent-up bars to investigate the effect of additional bars acting as shear reinforcement without sufficient anchorage length. The third series consisted of twelve specimens: Four specimens included bent-up bars with a sufficient anchorage length, two specimens included straight compressive reinforcement, two had only tensile reinforcement, and the last four included both tensile reinforcement and straight reinforcing bars passing through the column on the compression side of the slab. The tensile reinforcement was cut-off at specified points to ensure that it did not contribute to the shear transfer after punching failure. In this case, the only link between the punching cone and the rest of the slab is the compressive reinforcement and its influence on the post punching behavior is investigated. Table 1 presents the main parameters and mechanical properties of the specimens: ρ is the tensile reinforcement ratio, d is the effective depth of the slabs, A_{sb} is the area of the compressive reinforcement bars passing through the column, f_{sy} is the yielding strength and E_s is the modulus of elasticity of the reinforcing steel, f_c, f_{ct} and E_c are the compressive strength, the tensile strength and the modulus of elasticity of the concrete.

2.1 Geometry and reinforcement

All 24 slabs were identical in size and shape. The total width of the slabs was 1500 mm and the nominal total thickness of the slabs was h = 125 mm. A square steel plate of 130 x 130 mm was used to simulate a rigid column in all tests, see Figure 2. For all specimens, ϕ8 was used as the main diameter for the tensile reinforcement. The first four specimens were designed to investigate the effect of various reinforcement ratios on the post punching behavior of flat slabs. For PM-1 to PM-4, the bar spacing were 200, 100, 60 and 35 mm, respectively (ρ = 0.25%, 0.5%, 0.82% and 1.41%). For the remaining twenty specimens, the tensile reinforcement ratio was ρ = 0.82% (ϕ8 at 60 mm).

Table 1: Reinforcement detail and mechanical properties of materials for all test specimens

	Test	ρ [%]	*d* [mm]	A_{sb}	f_{sy} [MPa]	E_s [GPa]	f_c [MPa]	f_{ct} [MPa]	E_c [GPa]	*Detail of reinforcement*
Series 1	PM-1	0.25	102	-	601	202	36.6	2.9	36.9	
	PM-2	0.49	102	-	601	202	36.5	2.8	36.7	
	PM-3	0.82	102	-	601	202	37.8	3.4	37.9	
	PM-4	1.41	102	-	601	202	36.8	3.0	37.1	
Series 2	PM-9	0.82	102	4Ø8	601	202	31.0	2.3	33.3	
	PM-10	0.82	102	4Ø10	560	198	31.1	2.3	33.3	
	PM-11	0.82	102	4Ø12	547	201	32.3	2.5	33.7	
	PM-12	0.82	102	4Ø14	526	199	32.4	2.6	33.7	
	PM-13	0.82	102	4Ø8	601	202	32.6	2.6	33.8	
	PM-14	0.82	102	4Ø10	560	198	32.7	2.6	33.8	
	PM-15	0.84	100	4Ø12	547	201	32.7	2.6	33.8	
	PM-16	0.83	101	4Ø14	526	199	32.8	2.6	33.9	
Series 3	PM-17	0.82	102	4Ø8	625	201	39.7	2.8	28.7	
	PM-18	0.88	95	4Ø10	605	195	39.8	2.8	28.8	
	PM-19	0.85	99	4Ø12	566	195	39.9	2.8	28.8	
	PM-20	0.82	102	4Ø14	578	204	40.0	2.9	29.0	
	PM-21	0.81	103	4Ø8	625	201	40.2	2.9	29.3	
	PM-22	0.85	99	4Ø10	605	195	40.3	2.9	29.5	
	PM-23	0.88	95	-	566	201	40.4	2.9	29.7	
	PM-24	0.86	97	-	578	201	40.4	3.0	29.9	
	PM-25	0.85	98	4Ø8	625	201	40.4	3.0	30.1	
	PM-26	0.83	101	4Ø10	605	195	40.3	3.0	30.1	
	PM-27	0.81	104	4Ø12	566	195	40.3	3.0	30.2	
	PM-28	0.85	99	4Ø14	578	204	40.3	3.0	30.3	

For slabs PM-9, PM-10, PM-11 and PM-12, ϕ8, ϕ10, ϕ12 and ϕ14 were used as straight bars in the compression zone of the slab. For slabs PM-13, PM-14, PM-15 and PM-16, ϕ8, ϕ10, ϕ12 and ϕ14 bent-up bars were used as additional shear reinforcement with an angle of inclination of 30° and bent at a distance of 50 mm from the column face. For slabs PM-17, PM-18, PM-19 and PM-20, ϕ8, ϕ10, ϕ12 and ϕ14 bent-up bars were used, respectively. Contrary to the slabs PM-13 to PM-16, full anchorage condition was provided for PM-17 to PM-20. PM-21 and PM-22 were similar to PM-9 and PM-10 respectively, however for PM-9 and PM-10 cold-worked steel and for PM-21 and PM-22 hot-rolled steel was used. PM-23 and PM-24 were similar to PM-3. For PM-24, three closed stirrup were used over the column to investigate the effect of concrete confinement on the post punching behavior. Slabs PM-25, PM-26, PM-27 and PM-28 had ϕ8 at 60 mm as the tensile reinforcement, which was cut off at some specified points to investigate the effect of a short anchorage length of the tensile reinforcement. The anchorage length was equal to *2d, 2.5d, 3d* and *3.5d* respectively. In these specimens, ϕ8, ϕ10, ϕ12 and ϕ14 were used as straight bars in the compression zone of the slab specimens, respectively. In all specimens, very strong edge reinforcement in both top and bottom layer was provided to avoid unexpected modes of failure. For all slabs, the nominal concrete cover was 15 mm.

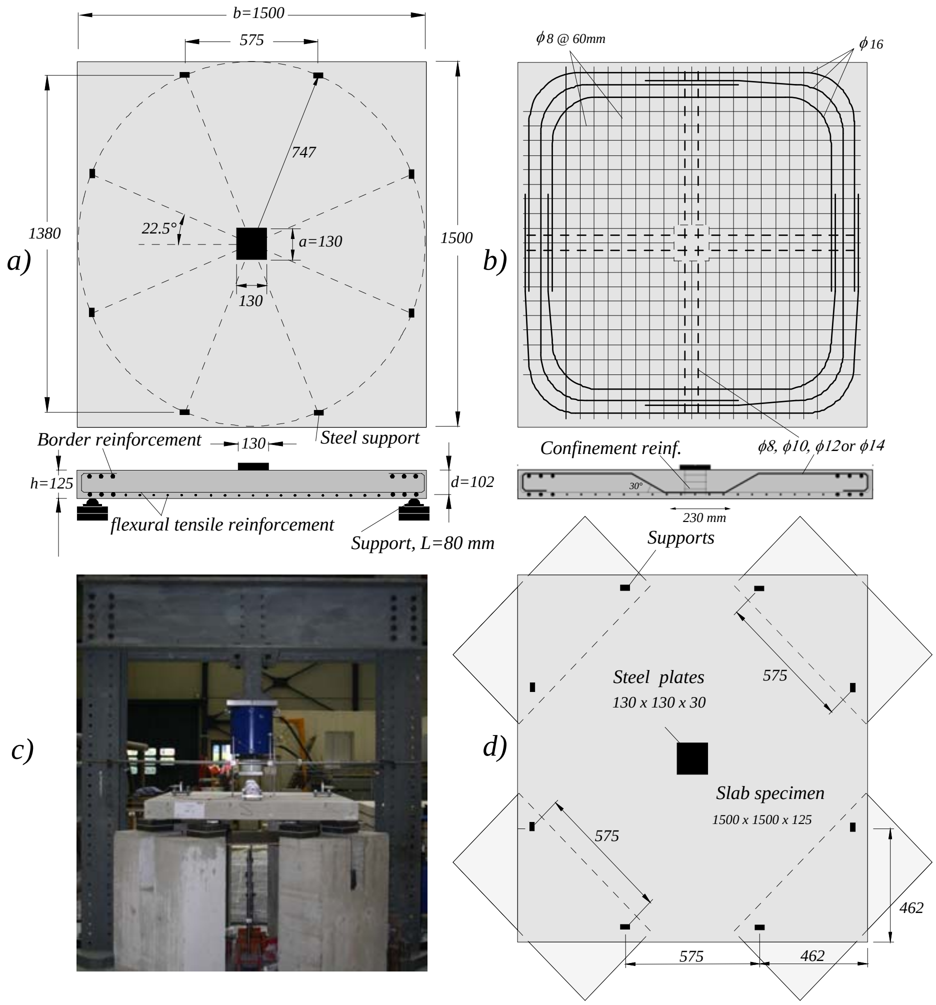


Figure 2: Reinforcement arrangement and test setup: a) typical slab plan and section (PM-3), b) reinforcement layout for PM-17 to PM-20, c) test setup, and d) test setup, plan view [mm][9]

2.2 Test results and comparisons

It was generally observed that after the punching shear strength has been reached, the load decreases rapidly. Then it started increasing with further deflection. At this stage, because of the large strains at the slab top surface, cracks propagate through the slab and yielding of reinforcement spreads throughout the slab. The load is carried by the reinforcement acting as a tensile membrane and with further deflection, the load carried increases until the reinforcement start to fracture.

Figure 3 compares the load - central deflection for slabs PM-12, PM-16, PM-20 (one slab for every reinforcement layout, with the same diameter of additional bars, ϕ=14) and PM-24 (without additional reinforcement) to show the influence of the various reinforcement layouts on the post punching behavior of flat slabs. To simplify this comparison, both vertical and horizontal axes are normalized. The maximum post punching strength V_{pp} was 245, 135, 345 and 101 kN and the ratio of the maximum post punching strength to the maximum punching strength V_p was 0.98, 0.45, 0.86 and 0.37 for slabs PM-12, PM-16, PM-20 and PM-24, respectively. For PM-16, the punching crack started from the face of the column and went through the slab and then propagated along the bent-up bar, leaving such shear reinforcement element ineffective. PM-20 had no anchorage problem and had a larger punching strength than the other slabs; however its post punching strength is less than that of PM-12. For slab PM-12, it was observed that using the straight steel bars passing through the column core makes it possible to reach nearly the punching strength of the slab (98%), showing that a means of preventing progressive collapse can be provided.

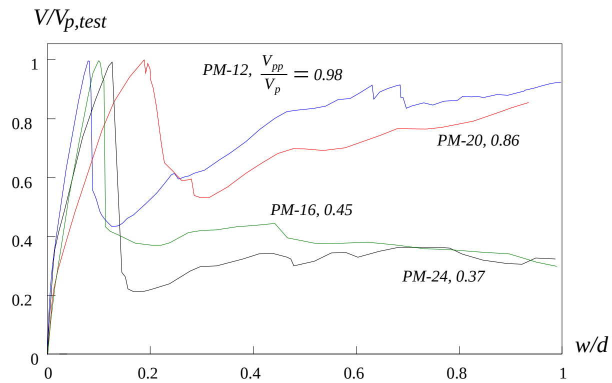


Figure 3: Post punching behavior of slabs PM-12, PM-16, PM-20 and PM-24

3. Mechanical model

The shear strength in concrete structures is provided by the shear transfer in the compression zone of concrete, aggregate interlocking across the crack surface, shear reinforcement and longitudinal reinforcement crossing the crack. As the load increases, cracks open, and aggregate interlock reduces quickly. Therefore, in absence of shear reinforcement, longitudinal reinforcing bars play a significant role in transferring shear, as other contributions to the shear transfer are fairly small. This is in particular the case of the post punching behavior of flat slabs supported by columns.

Because the only remaining link between the punching cone and the slab is the reinforcement, membrane effect caused by well anchored tensile reinforcement and dowel action caused by the compressive reinforcement passing through the column govern the overall post punching behavior of flat slabs. The relevant parameters affecting these two phenomena are the mechanical properties of the reinforcement and concrete, the bar diameter and spacing, and the angle of inclination of the punching cone.

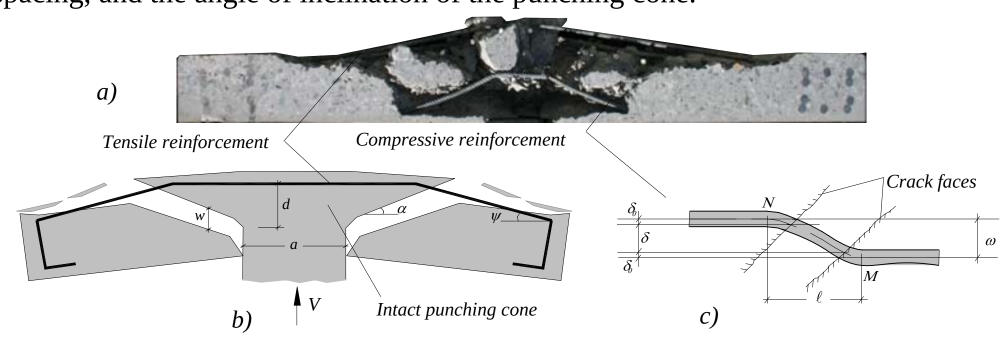


Figure 4: Post punching load carrying mechanism: a) slab PM-22 after post punching testing, b) simplified membrane effect mechanism, c) dowel action model

Membrane Effect: In the post punching phase, the slab undergoes very large deflections. Cracks on the tension face of the slab become wider and wider and the tensile reinforcement separates from the outer concrete shortly after punching. In absence of stirrups, it can be assumed that the well anchored tensile reinforcing bars tear out of concrete. Since the concrete cover is small, spalling of the concrete cover can be expected. Figure 4 shows a simplified mechanism of membrane effect with the position of a bar crossing the intact punching cone. The elongation of the steel bars can be obtained from geometrical considerations. Based on a bilinear stress-strain relationship for the reinforcing steel, the following relations were developed to predict the contribution of membrane effect to the post punching strength of flat slabs:

$$V_m(w) = \sum_1^n V_{mi}(w) \tag{1}$$

$$V_{mi}(w) = \begin{cases} E_s A_b (1/\cos\psi_i - 1)\sin\psi_i & \varepsilon_s < \varepsilon_y \\ f_{sy} A_b \sin\psi_i & \varepsilon_y < \varepsilon_s < \varepsilon_u \\ 0 & \varepsilon_s > \varepsilon_u \end{cases} \tag{2}$$

$$\tan\psi_i = 2w/(b - 2\sqrt{(0.5a + d\cot\alpha)^2 - s_i^2} \tag{3}$$

where V_m is the contribution of membrane effect to the shear transfer after punching, V_{mi} is the individual contribution of a bar to the shear transfer, w is the vertical displacement, a is column width, b is slab width, α is the angle of inclination of the punching cone, ε_s, ε_y and ε_u are the strain, yielding strain and ultimate strain of the steel reinforcement, s_i is the distance of the bar from the center of the slab, A_b is the section of the bar, and n is the number of bars crossing the punching cone.

Dowel action: Based on the observations during the tests, the deformed shape of a reinforcing bar can be assumed to be as a cubic function. To define the shape, four boundary conditions are needed. Considering δ_0, δ_ℓ, α_0, α_ℓ as displacements and rotations at points M and N (Figure 4) makes it possible to define the shape of a deformed bar after punching failure. Because the slabs tested in this investigation experienced very large deformations, the plastic deformations of the concrete supporting the bars (δ_0, α_0, α_ℓ) are negligible and can be assumed to be zero. Moreover, experimental results have shown[10] that, when the concrete cover c is greater than 6 to 8 times the bar diameter, the concrete supporting the bar does not crash, thus $\ell = (c + 8\ \phi)\ cot\alpha$. Calculating the elongation of a compressive reinforcing bar along the distance of ℓ, with a deflection of w, allows to determine the strains in the bar:

$$\varepsilon = \frac{1}{\ell}\int_0^\ell \sqrt{1 + (df/dx)^2 dx} - 1 \tag{4}$$

where $f(x)$ is the deformed shape of a reinforcing bar which was assumed as such a cubic function, and x is the distance from one side to another side of a critical punching shear crack. Consequently, the contribution of the compressive reinforcement to shear transfer is

$$V_d = \begin{cases} A_{sb}\varepsilon E_s \sin\beta & if \quad \varepsilon < \varepsilon_y \\ A_{sb} f_{sy} \sin\beta & if \quad \varepsilon_y < \varepsilon < \varepsilon_u \\ 0 & if \quad \varepsilon > \varepsilon_u \end{cases} \tag{5}$$

where f is the cubic function, V_d is the contribution of the compressive reinforcement to the shear transfer after failure and β is the angle of inclination of the reinforcing steel bars in the vicinity of the punching shear crack after failure. The post punching model is the combination of the membrane effect and dowel action:

$$V = V_m + V_d \tag{6}$$

Figure 5a shows a comparison between a typical test result, PM-12, with the proposed analytical model. Figure 5b compares the results of all post punching tests with the theoretical value predicted by the model and shows a good agreement. Improvements are still needed, however, and will be achieved by including the effect of strain hardening, of the bond-slip relationship, of concrete softening, of local punching failure of the steel bars and of the destruction of the punching cone.

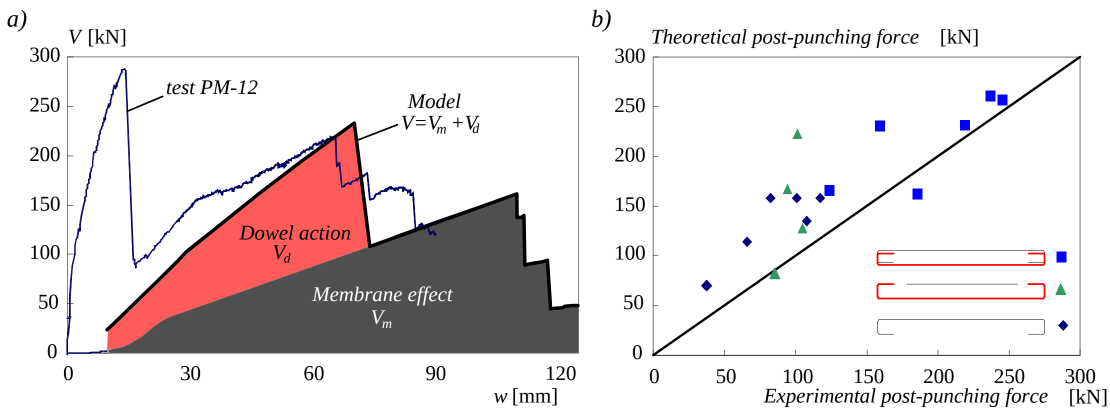


Figure 5: Mechanical model: a) a typical test result PM-12 in comparison with the proposed model, b) comparison of the experimental and theoretical results

4. Conclusions

To gather additional information on the subject of post punching, a total of 24 specimens were tested in post punching in the laboratory. The effect of tensile reinforcement, compressive reinforcement passing through the column, bent-up-bars and anchorage details were investigated. The results show the possibility of increasing the post punching strength of slab-column connections without using special shear reinforcement.

The test results show that the reinforcing bars play an important role in the strength after punching because they are the only remaining link between the punching cone and the rest of slab. As a consequence, the main load-carrying effects that take place after punching are the membrane effect in the anchored tensile reinforcement and the dowel action of the bottom reinforcement crossing the column. These two phenomena are mainly controlled by the amount and strength of the reinforcement. The way it is anchored, the strength of the concrete and the possible inclination of the reinforcing bars are additional parameters.

A mechanical model was developed to predict the post punching behavior of flat slabs supported by columns. The model is able to predict the post punching strength and deformation of a flat slab.

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